Metallicity Dependence of the Cepheid Calibration

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The metallicity dependence of the Cepheid period-luminosity (PL) relation has been a controversial issue. The more commonly accepted view is that the PL relation is insensitive to metal abundance, while the period-luminosity-colour relation is fairly sensitive, as indicated by stellar pulsation models[1−4] (see also refs. 5,6). The direct observational evidence is scanty, however. Freedman and Madore[7] have studied Cepheids in three regions having different metallicity in M31 and concluded no statistically significant residual differences in the distance moduli. On the other hand, Gould[8] has claimed that the data of Freedman and Madore are rather indicating a large metallicity dependence $\Delta\mu/\Delta[\mathrm{Fe/H}] = 0.88\pm0.16$, where μ is the distance modulus derived from the Cepheid PL relation. A moderate metallicity dependence $\Delta\mu/\Delta[\mathrm{Fe/H}] = 0.44$ was also concluded in a recent report from EROS photometry for the Magellanic Clouds[9].

Recently an accurate measurement of metallicity has been carried out for 23 Galactic Cepheids by Fry and Carney[10] (hereafter FC). This work has given us an opportunity to examine the metallicity dependence of the Cepheid PL relation and its calibrations. The most commonly used calibration of the Galactic Cepheids is probably that of Feast and Walker[11] based on V band photometry and the distance based on the ZAMS fitting to the clusters that contain the Cepheids. Laney and Stobie[12] (hereafter LS) have slightly updated the Feast-Walker distance and also provided a calibration of the Cepheid PL

relation for the near infrared JHK colour bands[13] in addition to that for the V band (their result for V band hardly differs from that of Feast and Walker). The work of LS may perhaps be taken as the most accurate calibration of the Cepheid PL relation to date, hence giving the most accurate distance to the LMC with the Cepheid method.

The FC sample contains 12 Cepheids in common with the LS sample: EV Sct, V340 Nor, WZ Sgr, V Cen, SW Vel, CV Mon, S Nor, U Sgr, TW Nor, SV Vul, QZ Nor, and T Mon in the order of increasing metallicity. We show in Fig. 1 an uncritical display of the residual of the fit to the Cepheid PL relation as a function of metallicity [Fe/H]. The residual is defined by

$$\delta M_\lambda = M_\lambda - (A_\lambda \log P + \phi_{\lambda PL}), \quad \lambda = V, J, H, K \tag{1}$$

with the coefficients given in LS: $(A, \phi) = (-2.874, -1.197)$ for V, $(-3.306, -1.971)$ for J, $(-3.421, -2.243)$ for H and $(-3.443, -2.297)$ for K (we take the first set of their parameters, but other choices hardly modify the plot of Fig. 1). Virtually the same plot is obtained with the data and the fit given in Feast and Walker for the V band. The error of the metallicity measurement of FC is $\pm(0.02 - 0.03)$ dex except for SV Vul (±0.04) and CV Mon (±0.06). This figure shows a conspicuous correlation of M_λ with metallicity. The surprising fact is that this metallicity dependence is disturbingly large $\delta M_\lambda/\delta[\mathrm{Fe/H}] = -(1.3 - 1.4)$, almost independent of the colour band from V to K. We note that one highly deviated point (TW Nor) suffers from a very large reddening correction $E_{B-V}(\mathrm{OB}) = 1.34$ and M_V may not be accurately determined. The leftmost point EV Sct and QZ Nor (the second point from the right) are suspected to be overtone pulsation (FC). If we remove these three Cepheids (this means we remove all highly scattered points in Fig. 1), the metallicity gradient is $\delta M_\lambda/\delta[\mathrm{Fe/H}] = -(1.7-2.1)$. In order to underscore the colour independent nature of the offset we plotted δM_λ ($\lambda = V, J, H$) versus δM_K in Fig. 2.

Now the question arises as to whether this large metallicity dependence represents that

of the intrinsic Cepheid PL relation or it arises from some other artefacts of procedures used in estimating M_λ. Let us remember that the absolute magnitude is calculated with

$$\mu_0 = \mu_V - R(\mathrm{OB})E_{B-V}(\mathrm{OB}) \tag{2}$$

and

$$M_\lambda = m_\lambda - (A_\lambda/A_V)R(\mathrm{Cepheid})E(\mathrm{Cepheid}) - \mu_0 \qquad (3),$$

where the V band modulus μ_V is obtained by ZAMS fitting assuming the cluster metallicity [Fe/H]=0 (see e.g., refs. 11, 14). The ZAMS track with lower metallicity generally yields fainter magnitude for given colour (e.g., ref. 15) and hence this is just opposite to the trend observed in Fig. 1: a metallicity correction for the ZAMS fitting would steepen the slope. It is unlikely that the metallicity dependence arises from the absorption correction for Cepheids in eq. (3), because the correlation seen in Fig. 1 is wavelength independent, whereas reddening is not. Then we are left with two possibilities:

(i) the Cepheid PL relation indeed has a large metallicity dependence, or

(ii) the absorption correction for μ_0 has a large [Fe/H] dependence.

Case (i), if it does not looks very likely, does not conflict with any other observations, when the uncertainties in separating absorption corrections from the metallicity effect and also of the metallicity measurements are considered. The indicated metallicity dependence, however, is by more than a factor 10 larger than the prediction of the theoretical models of the Cepheid pulsation[1−4]. The colour-band independence of the offset at first glance also looks a little unusual from a theoretical view point. This is not impossible, however, if the *coefficient* of the pulsation equation (P as a function of mass and radius) is strongly affected by metal abundance, in contrast to what stellar model calculations suggest.[1,3] We remark that the sign of the period shift is consistent with the Oosterhoff period shift for RR Lyr,[16,17] for which stellar models also predict the metallicity dependence by a factor of > 10 smaller than observed.[18] If case (i) is true, an on-going Hubble Space Telescope

project for studying the metallicity dependence for Cepheids in M101[19] should detect the effect; the raw distance moduli derived from inner and outer regions may differ by 1 mag after absorption correction.

In order to examine the model prediction for the metallicity dependence of the period-colour (PC) relation, we show in Fig. 3 the residual of the fit of $(B-V)_0$ obtained by LS as a function of [Fe/H], and compare it with a prediction of Stothers.[3] Unfortunately, the scatter of data is too large that one can hardly conclude whether the residual shows the metallicity dependence. The only conclusion one can draw from the figure is that the metallicity effect on the PC relation, if any, is not too much larger than the theoretical model predicts. However, this does not preclude the possibility that the pulsation equation is strongly affected by metal abundance: the contribution of the metal-abundance dependent term to the zero point of the PC relation is one order of magnitude smaller than that to the zero point of the PL relation (see ref. 3). Namely, this test does not serve for us to choose among the two possibilities.

The colour independent nature may also be taken to be consistent with case (ii). Namely, either selective extinction E_{B-V}(OB), which is usually estimated from cluster reddenings or space reddenings of stars close to Cepheid, or R factor, which is set to be a constant, receives a large abundance effect, although, this differs from our conventional belief that the extinction correction for B stars does not depend so strongly on metallicity, for line blanketing effect is smaller for high temperature stars. Also somewhat strange with this case is that the extinction correction in (1) does not tend to cancel against that in (2) for the V band. We have examined possible correlation between E(OB), E(Cepheid) or $\mu_V - \mu_0$ and [Fe/H], but have not found any apparent correlations between those quantities.

One may suspect a systematic error in FC in estimating metallicity. One of the suspects may be in their estimate of temperature. We have checked that their values of [Fe/H] do not show any significant correlation with colour $(B-V)_0$, indicating no obvious

errors in the temperature estimate that correlates with metallicity. Indirect, but more significant is Fig. 2 which demonstrates a strong correlation among residuals of fitting in different colour bands, pointing towards a systematic problem in the Cepheid work itself, rather than in the estimate of metallicity of FC. (We remark that similar correlations in the residuals are noted in refs. 8 and 9.) Namely, possible systematic error of FC, if any, does not account for the entire problem posed here.

Neither of the two cases discussed above looks very likely, but certainly not impossible. If (i) is correct, the period-luminosity relation for the Cepheid is represented better with the addition of a metallicity term, for example for the V and K bands, such as

$$M_V = -1.256(\pm 0.046) - 2.874 \log P - 2.15(\pm 0.44)[\mathrm{Fe/H}] \quad (\sigma = 0.111) \tag{4a}$$

$$M_K = -2.385(\pm 0.039) - 3.443 \log P - 1.72(\pm 0.38)[\mathrm{Fe/H}] \quad (\sigma = 0.095) \tag{4b}$$

as obtained by fitting our 9 Cepheids (the slope is fixed to be that from LMC; EV Sct, QZ Nor and TW Nor are excluded). These are compared with

$$M_V = -1.144(\pm 0.077) - 2.874 \log P \qquad (\sigma = 0.232) \tag{5a}$$

$$M_K = -2.295(\pm 0.063) - 3.443 \log P \qquad (\sigma = 0.189) \tag{5b}$$

without the metallicity term (these equations agree with what are given in LS within the error). The equation with the metallicity term yields the LMC distance 0.4 mag *smaller* than estimated in LS for average metal abundance of the LMC, [Fe/H]=–0.3. If (ii) is correct the "true" PL relation after correcting for the metal abundance effect on μ_0 is given by the equation with the third term absorbed into eq. (4). A comparison of (4) with (5) indicate that the LMC distance may be $\approx$+0.1 mag *larger*. This shows that one cannot determine the distance accurately from the Cepheid PL relation unless the metallicity effect is well controlled.

A positive aspect, on the other hand, is that the intrinsic scatter of the Cepheid PL relation should substantially be smaller than is believed now once the metallicity correction is made. After the metallicity correction the dispersion of the PL relation becomes 0.08–0.11 mag depending on the colour band, which is about a half the scatter obtained by LS.

The present authors were unable to penetrate into details of the numbers obtained by LS beyond the point which is explicit in their paper. It is, however, obvious that the best present data used for the Cepheid calibration, which is a cornerstone of the extragalactic distance scale, contains an unusually large metallicity dependence that has been ignored in the literature. This would bring a significant uncertainty into the LMC distance; the error of the LMC distance from the Cepheid PL relation remains uncertain as large as –0.4 to +0.1 mag, till this problem is solved.

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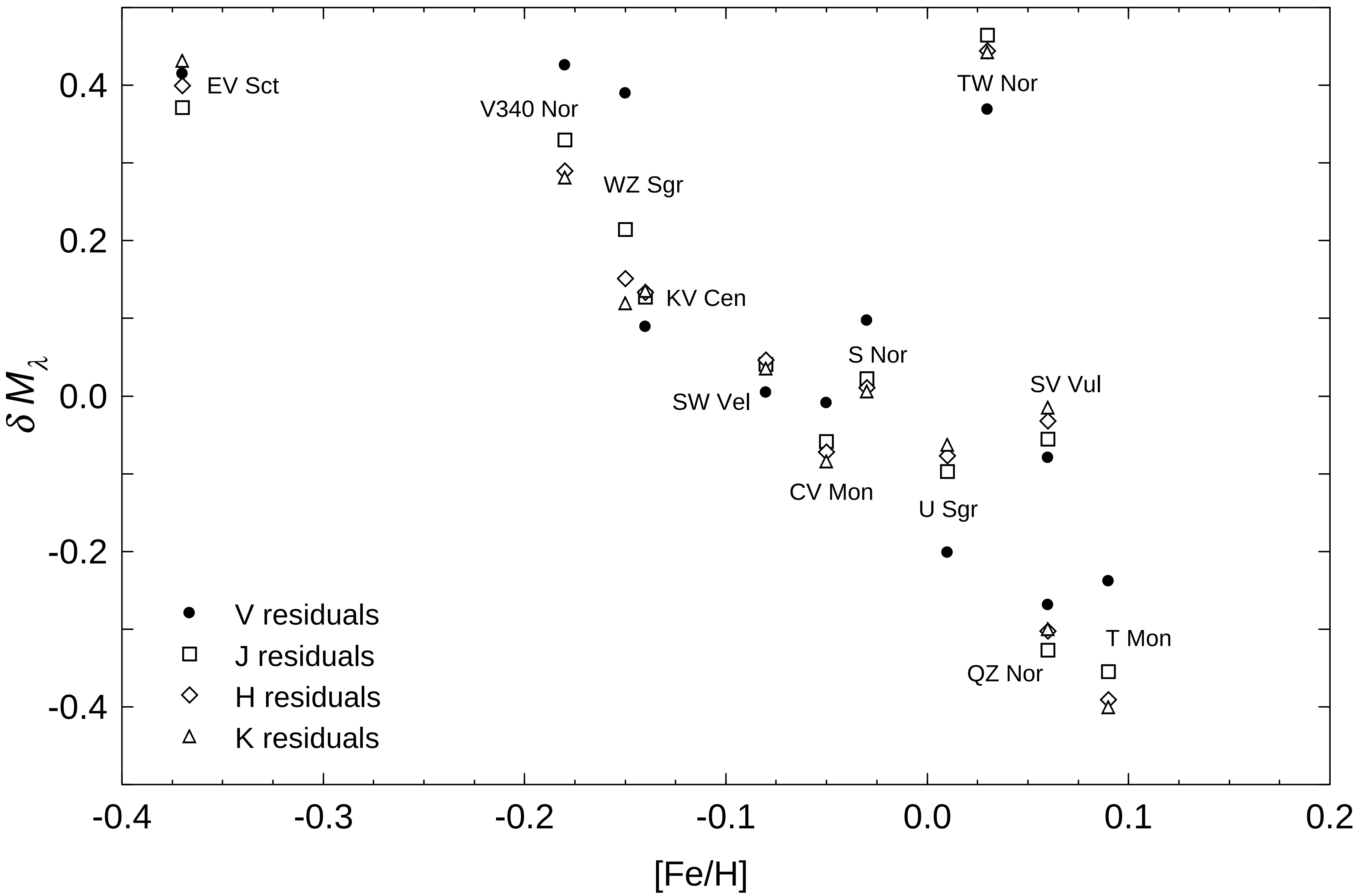
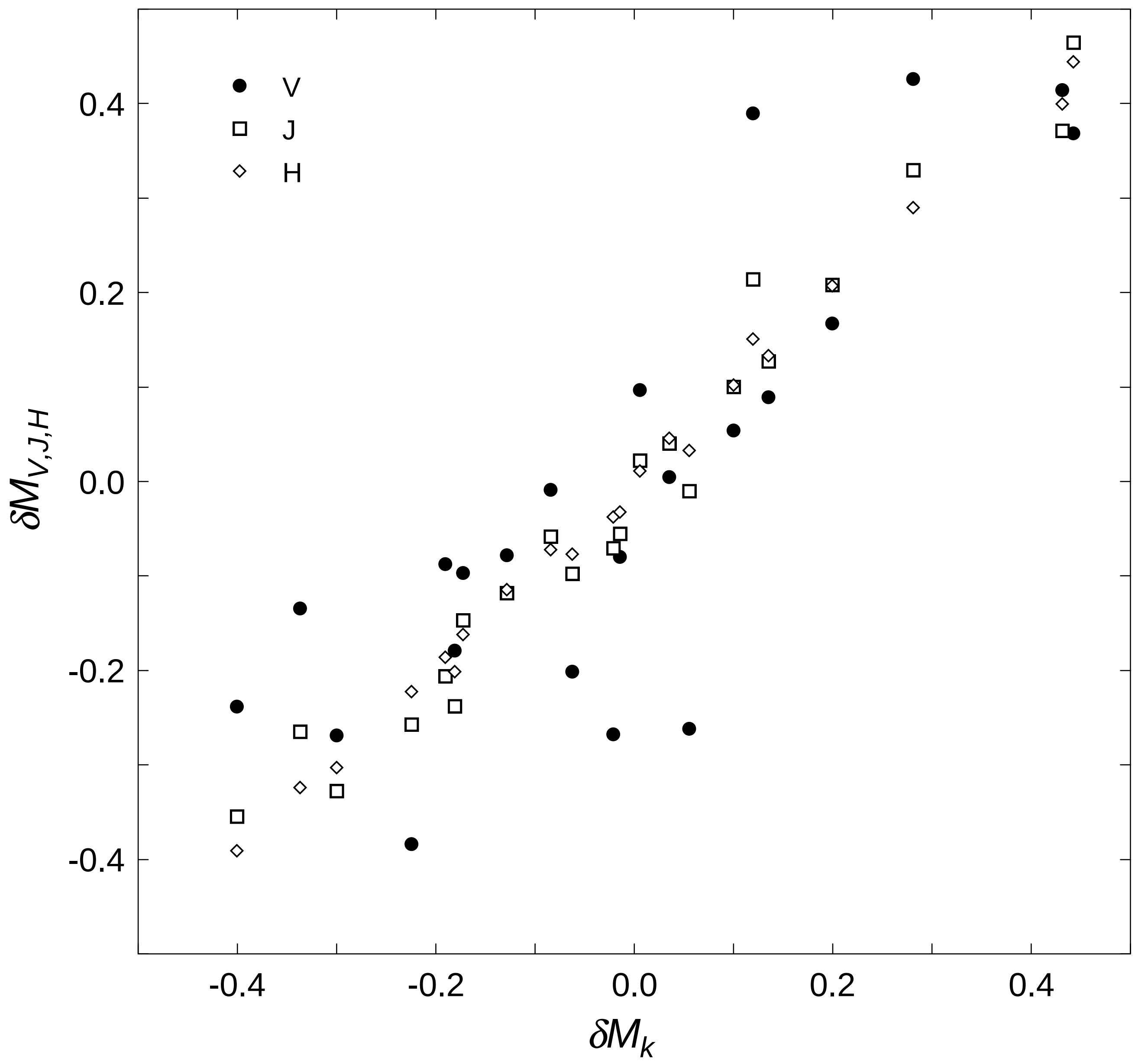
Figure captions

Fig. 1 Residual of the fit to the Cepheid PL relation as a function of metal abundance [Fe/H]. Here the residual is defined by $\delta M_\lambda = M_\lambda - (A_\lambda \log P + \phi_{\lambda PL})$ $(\lambda = V, J, H, K)$ with the coefficients A and $\phi_{\lambda PL}$) taken from LS together with the data of M_λ.

Fig. 2 Correlation of the residuals for different colour bands. $\delta M_V, \delta M_J$ and δM_H are plotted against δM_K.

Fig. 3 Residual of the fit to the Cepheid period-colour $(B - V)$ relation as a function of metal abundance. The residual is defined by $\delta(B-V)_0 = (B-V)_0 - (C \log P + D)$. Both coefficients and data are taken from LS. The curve shows $\delta(B-V)_0 \simeq 8.4\delta Z$ as predicted by Stothers.[3]


EV Sct
V340 Nor
WZ Sgr
KV Cen
TW Nor
S Nor
SW Vel
CV Mon
SV Vul
U Sgr
T Mon
QZ Nor
V residuals
J residuals
H residuals
K residuals
0.4
0.2
0.0
-0.2
-0.4
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
[Fe/H]
δM_λ



V
J
H
0.4
0.2
0.0
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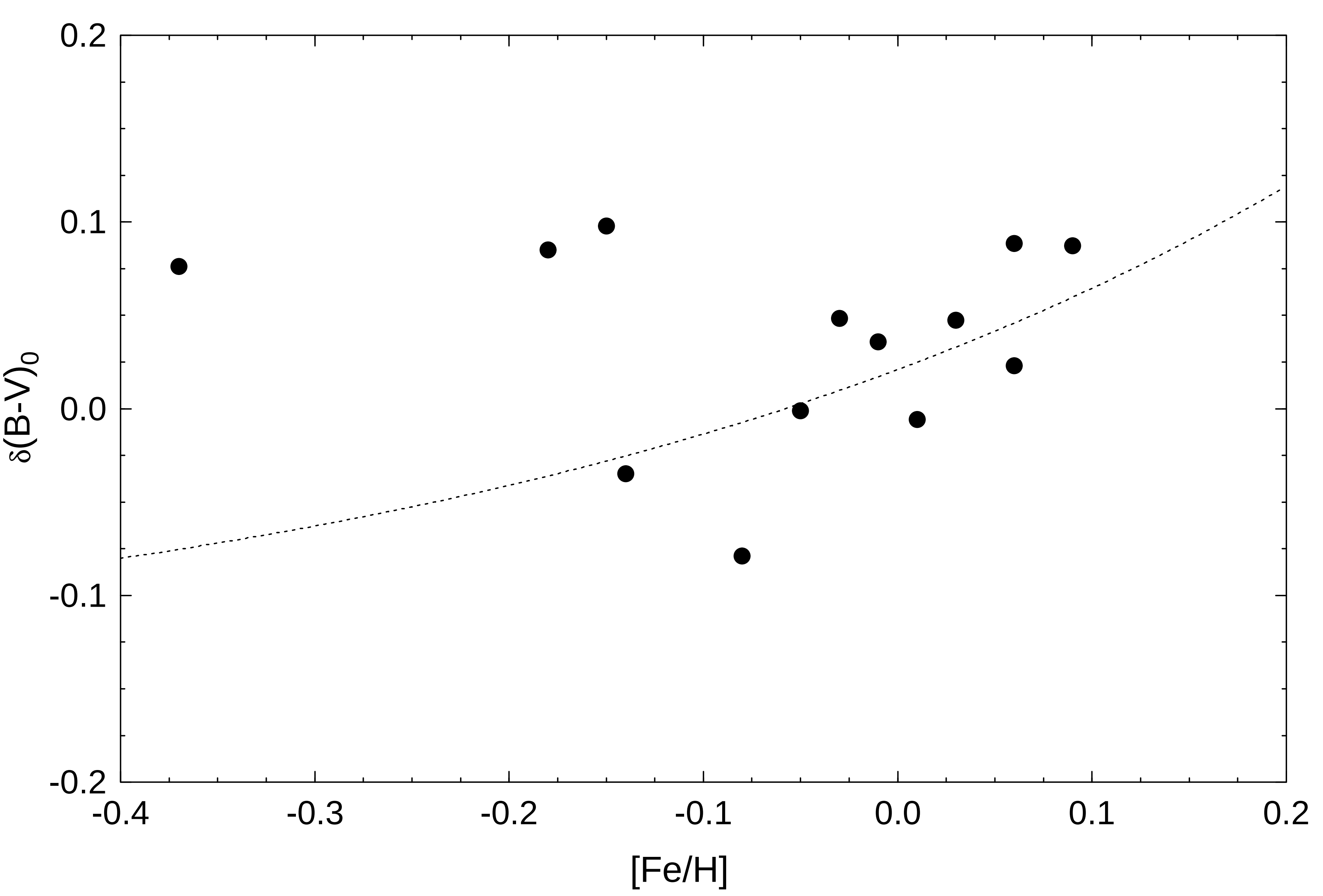
0.4
$\delta M_{V,J,H}$
δM_k



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-0.1
-0.2
δ(B-V)0
-0.4
-0.3
-0.2
-0.1
0.0
0.1
0.2
[Fe/H]